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Estimating the benefit of quarantine: eradicating invasive cane toads from islands

Adam S. Smart[1], Reid Tingley[1,2], Ben L. Phillips[1]

1 *School of BioSciences, University of Melbourne, Parkville, VIC, 3010, Australia* **2** *School of Biological Sciences, Monash University, Clayton, VIC, 3800, Australia*

Corresponding author: Adam S. Smart (asmart1@student.unimelb.edu.au)

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Abstract

Islands are increasingly used to protect endangered populations from the negative impacts of invasive species. Quarantine efforts on islands are likely to be undervalued in circumstances in which a failure incurs non-economic costs. One approach to ascribe monetary value to such efforts is by modeling the expense of restoring a system to its former state. Using field-based removal experiments on two different islands off northern Australia separated by > 400 km, we estimate cane toad densities, detection probabilities, and the resulting effort needed to eradicate toads from an island. We use these estimates to conservatively evaluate the financial benefit of cane toad quarantine across offshore islands prioritized for conservation management by the Australian federal government. We calculate density as animals per km of freshwater shoreline, and find striking concordance of density estimates across our two island study sites: a mean density of 352 [289, 466] adult toads per kilometre on one island, and a density of 341 [298, 390] on the second. Detection probability differed between our two study islands (Horan Island: 0.1 [0.07, 0.13]; Indian Island: 0.27 [0.22, 0.33]). Using a removal model and the financial costs incurred during toad removal, we estimate that eradicating cane toads would, on average, cost between $22 487 [$14 691, $34 480] (based on Horan Island) and $39 724 [$22 069, $64 001] AUD (Indian Island) per km of available freshwater shoreline. We estimate the remaining value of toad quarantine across islands that have been prioritized for conservation benefit within the toads' predicted range, and find the net value of quarantine efforts to be $43.4 [28.4–66.6] – $76.7 [42.6–123.6] M depending on which island dataset is used to calibrate the model. We conservatively estimate the potential value of a mainland cane toad containment strategy – to prevent the spread of toads into the Pilbara Bioregion – to be $80 [52.6–123.4] – $142 [79.0–229.0] M. We present a modeling framework that can be used to estimate the value of preventative management, via estimating the length and cost of an eradication program. Our analyses suggest that there is substantial economic value in cane toad quarantine efforts across Australian offshore islands and in a proposed mainland containment strategy.

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Keywords
Cane Toad, density, detection probability, eradication, islands, quarantine

Introduction

It is a truth universally acknowledged that an ounce of prevention is worth a pound of cure. In alien invasive species management, prevention of impact is achieved by conducting routine surveillance programs aimed at early detection (Holden et al. 2015), and by minimizing human-mediated dispersal of non-indigenous species (Chen et al. 2018). Despite the regular use of such quarantine approaches, conservation managers rarely explicitly value this preventative management. Preventative measures are increasingly being adopted to save imperiled taxa (Burns et al. 2012; Commonwealth of Australia 2015), but without explicitly valuing these efforts, we risk falling prey to cognitive biases (e.g., immediacy bias) and so will tend to commit substantially more money and effort to tactical, "cure" type approaches, than to strategic "prevention". Indeed, vastly more resources are spent controlling the spread and impact of invaders than are spent on preventing their arrival and establishment (Hoffman and Broadhurst 2016).

Quarantine is particularly likely to be undervalued in circumstances in which a failure incurs non-economic costs (e.g., biodiversity loss) (Leung et al. 2002) or when costs or damages persist over long-time scales (Epanchin-Niell et al. 2015). In cases where restoration is feasible, one way to place monetary value on such quarantine efforts is to calculate the cost of restoring the system to its former state (Kimball et al. 2014; Rohr et al. 2016). In the case of an invasive species with primarily non-economic impacts, where invasion is certain or extremely likely, we can calculate the ongoing benefit of quarantine as this expense, i.e., a subsequent eradication program. Such a valuation is a lower bound on the benefit of quarantine for a number of reasons. First, the same quarantine effort typically protects against many potential invasive species, while eradication costs would apply separately to each species. In addition, any impact that an invasive species has before it is eradicated (e.g., local extinction of a native species) must be added to the cost of restoration (Hoffmann and Broadhurst 2016; Jardine and Sanchirico 2018). Lastly, as more area is invaded the value ascribed to remaining quarantined areas will be of greater value. Thus, the cost of eradicating a single invader is a very conservative estimate of the true value of quarantine efforts. Given the above it is important to note that it is unlikely that all potential islands will be invaded, and as such, the estimated costs of eradication have the potential to be significantly lower than 'worse case' cost modeling. Even in the face of reduced costs it is prudent to recognize the likelihood that governments and land managers will respond to the large eradication cost of inaction, or the withstanding preference to attempt eradication when incursions inevitably happen.

Islands are important resources for conservation quarantine because they offer a natural barrier to the spread of invasive species. Conservation biologists routinely exploit this property of islands, not only to protect species that naturally occur on

islands, but also to provide refuge for species under threat on the mainland (Thomas 2011; Tershy et al. 2015; Legge et al. 2018). In Australia alone, a minimum of 47 conservation translocations to islands have been carried out to date (Department of the Environment, Water, Heritage and the Arts 2009). In these circumstances – where the conservation value of an island has been artificially bolstered – the subsequent arrival of invasive species can have a larger impact than they otherwise would. Typically, island quarantine is used by conservation managers to protect native species from wildlife disease (e.g, Tasmanian devil facial tumor disease; McCallum et al. 2009) or invasive predators (e.g., foxes, cats, weasels, rats). In Australia, however, islands are also used to mitigate the impact of cane toads (*Rhinella marina*) on native predators (Moro et al. 2018; Ringma et al. 2018). Cane toads were introduced to northeastern Australia in the 1930s and, in northern Australia, continue to spread westerly at a rate of ~50 km per year (Phillips et al. 2010). This invasion has had major impacts on populations of native predators, many of which have no resistance to the toad's toxin (Greenlees et al. 2010; Nelson et al. 2010; Llewelyn et al. 2014). In response to declines of multiple predator species (e.g., dasyurids, monitors, snakes) the Australian government implemented the Cane Toad Threat Abatement Plan (2011), which aimed to identify, and where possible reduce, the impact of cane toads on native species (Shanmuganathan et al. 2010). A lack of viable methods for broad-scale control, however, has since led the Australian government to place an increased emphasis on containment (on the mainland) and on quarantine (on offshore islands) to mitigate the biodiversity impacts of cane toads (Tingley et al. 2017).

While quarantine is currently the best available strategy, it is not a panacea: cane toads have already established themselves on at least 48 islands across northern Australia (McKinney et al. 2018 unpub data), with potential for further self and anthropogenic introductions. In addition, whilst many methods are being proposed to combat the spread of toads, the most likely control method is quarantine (Tingley et al. 2017), possibly aided by targeted gene flow. Thus, execution of the strategy outlined in the Cane Toad Threat Abatement Plan requires ongoing quarantine, eradication, and containment efforts. Here we estimate the lower bound of the monetary value of these ongoing efforts by estimating the effort required to eradicate cane toads from two islands in northern Australia and generalizing this cost to islands and areas that are currently free of toads. We approach this problem by estimating the density and detection probability of toads on each island and use these estimates to calculate the amount of time and money it would take to remove toads across a subset of islands prioritized for conservation in Australia.

Materials and methods

Study Area

This study was carried out on two islands in northern Australia: Horan Island on Lake Argyle, Western Australia and Kabal (Indian Island) in the Northern Territory. Lake

Argyle, located within the East Kimberly region, is Western Australia's largest constructed reservoir covering > 880 km^2. The study site is composed of exposed spinifex-covered hilltops and sparse savanna woodland. Freshwater is available year-round, with the lake contracting from May–November. Toads are thought to have colonized islands on the lake in the wet seasons of 2009/2010 (Somaweera and Shine 2012). Indian Island is an offshore island, 40 km west of Darwin in the Northern Territory. It supports predominantly savanna woodland and monsoonal vine thicket, with a large ephemeral freshwater swamp located on the northern tip of the island. Depending on the magnitude of the wet season, standing water can be present in this swamp year-round or dry up by late September. Toads are thought to have colonized Indian Island via rafting events around 2008. Access to Indian Island was granted by Kenbi Traditional Custodians (Northern Land Council permit 82368).

Field sampling

Cane toad surveys occurred over six nights, on each island, denoted, $t = \{0, 1, ..., 5\}$, during November 2017 (Horan Island) and October 2018 (Indian Island). Surveys commenced at sundown each evening and lasted four hours, with ambient temperatures ranging from 24–35 °C. As Horan Island sits within a freshwater lake, the entire island was walked around each night (7.6 km) by two people using head torches; one individual focused on the higher part of the shoreline, the other on the lower shoreline. Indian Island is an oceanic island, with the northern half (an area of 6.28 km^2) separated from the southern half by a tidal saltmarsh. The island contains a single freshwater swamp present in the dry season (circumference of 1.1 km). This swamp was navigated each night by two people using head torches over a period of four hours, with shoreline areas being surveyed more than once each night due to the reduced shoreline. On both islands, every toad encountered was collected and humanely killed on site in accordance with The University of Melbourne animal ethics protocol (1714277.1) and State laws regarding handling of non-native species. Each night, we recorded the number of individual toads collected, c_t. Surveys were conducted immediately prior to the breeding season so that only post-metamorphic age classes were encountered.

Statistical analysis

We do not encounter every individual on a given night, and so incorporate imperfect detection. For each island, we aim to estimate two parameters: N_0, the true number of toads on the island at the commencement of surveys and p the mean per-individual detection probability. Due to our experimental design we hold p constant across time but recognize that adding variance in p will likely increase costs. We can then use these to estimate α, the length of time (in days) required to eradicate toads from our treat-

ment areas. The number of individuals collected each night, c_t, can be considered a draw from a binomial distribution:

$$c_t \sim \text{Binom}\left(N_t, p\right).$$

Where N_0, the pre-sampling population size, is a latent variable with a mean and variance equal to λ, such that:

$$N_0 \sim \text{Pois}(\lambda).$$

For $t > 0$:

$$N_t = N_0 - \sum_0^{t-1} c_t.$$

We used a Jefferys prior (Jefferys 1961) to model our prior distributions for p (beta (0.5,0.5)). We specify λ as uniform between 200–10 000 (Indian Island) or 1500–10 000 (Horan Island) respectively. The lower bound of priors for λ are informed by densities of cane toads in their native range (Lampo and Bayliss 1996) and represent a conservative lower bound.

The length of time required to remove a population, α from a treatment area is described via the relationship:

$$\alpha = \frac{\ln\left(r_{crit}\right)}{\ln(1-p)},$$

where, r_{crit}, the critical removal threshold (i.e. the proportion of the population remaining if there are less than two individuals left), is equal to $1/N_0$ (see Suppl. material 1: File S1 for workings).

Models were fitted with Markov chain Monte Carlo (MCMC) in JAGS v.4.6.0, run through R v3.4.1 via the package rjags v4.6.0 (Plummer 2013). Three model chains were run for 30,000 iterations, with the first 10,000 iterations discarded as a burn-in, which was sufficient for the MCMC chains to converge. Convergence was checked using the Gelman-Rubin diagnostic (Gelman and Rubin 1992); all chains produced potential scale reduction factors < 1.1, indicating convergence of chains. The remaining samples were thinned by a factor of 2, resulting in 10,000 samples per chain for post-processing.

We denote a successful eradication to have occurred when only a single toad remains (i.e., no further breeding pairs remain). In order to successfully eradicate a population, the number of immigrants (i.e., propagule pressure) must be controlled prior to eradication efforts. We assume that our system is closed for the six consecutive nights of sampling. We then apply the outputs of our model to estimate the removal cost of toads across a range of Australian islands, under the assumption that immigration is zero for the duration of any subsequent eradication program.

Cost analysis

We estimate the cost of eradicating toads on prioritized islands (see below) from incurred personnel, consumable, and travel costs during toad collection (Table 1). Relative to most islands across northern Australia, both Horan and Indian Islands are readily accessible, thus our travel costs are modest. We assume that eradication is conducted by a fully equipped organization; thus, we do not include vehicle/boat purchase or hire (i.e., set-up costs), nor do we consider organizational in-kind associated with utilizing existing capital. Removal efforts are carried out in subsequent five-day blocks until eradication is reached; and we assume that travel to and from our site is incurred weekly in order to resupply staff. Travel costs include a $85/hour consultant rate (for travel time) plus the additional costs of fuel, insurance, and vehicle maintenance (an extra $36/hour). Thus, total travel costs are $111/hour of travel. For Horan Island we assume a travel duration of four hours each way (to and from Katherine). For Indian Island the travel time is also four hours each way (to Darwin).

Cost Scenarios

We use our estimates of the length of time required to eradicate toads from our treatment areas on Horan and Indian Islands (with their attendant detection probabilities) to explore the potential of quarantine efforts on a subset of high priority islands (Table 2). Our chosen islands are drawn from a list of 100 oceanic islands that the Australian Commonwealth has prioritized for conservation, due to their biodiversity

Table 1. Example areal metric costing and assumptions associated with a cane toad eradication program on Horan Island. Derived from incurred field costs and estimated mean removal estimates (75 days). All figures are in Australian Dollars ($AU).

Item Description	Item Category	Unit type	Number of units	Cost per unit	Total Cost	Assumption
Conducting toad surveys/removal	Personnel	Per hour	1500	$85	$127 500	Hourly rate of $85. Removal efforts are based on two people each getting paid for ten hours a day at survey rates.
Motorized travel to and from study site	Travel	Per hour	120	$111	$13 320	Hourly rate of $111 per hour of vehicle use (survey rate, insurance, maintenance and fuel). Return travel nearest town is 4 hours. Field member returning to town to resupply once per week (75 days/5 = 15 trips of 8 hours).
Motorized travel within site	Travel	Per hour	75	$36	$2 700	Additional hourly rate of $36 per hour of in-site vehicle use. This captures insurance, maintenance and fuel costs. One hour of in-site travel each day.
Food and sustenance	Consumable	Per day	75	$60	$4 500	Food at $30 per head, per day.
AA Batteries for night surveys	Consumable	Per four	75	$14	$1 050	Single set of batteries required for each sampling night.
Refill of CO_2 canister (8kg)	Consumable	Per canister	1	$150	$150	Single canister required for euthanizing cane toads.
Calico Bags for holding individuals	Consumable	Per bag	63	$1	$63	A Calico bag required for every 20 individuals removed (n = 1251).
Theoretical cost to eradicate cane toads from Horan Island (0.78km²)					**$149 283**	

Table 2. Islands included in analyses from the top 100 islands prioritized by the Australian Commonwealth for conservation actions (Department of the Environment, Water, Heritage and the Arts (2009)). Estimates for the benefit of quarantine are in '000s (AUD). Mean benefit reports the cost of removal, averaging over costs calculated with the detection probabilities of each of our island systems.

Jurisdiction	Island Name	Toads Present	Distance to mainland (km)	Area (km^2)	Length of freshwater shoreline (km)	Mean benefit of quarantine (000s)	Lower Est.	Upper Est.
New South Wales	Lord Howe Island	No	570	11	1	18	10	28
Western Australia	Barrow Island	No	56	139	21	373	200	580
	Bernier Island	No	38	171	2	36	19	55
	East Intercourse Island	No	5.5	51	2	36	19	55
	Faure Island	No	6.1	8	2	36	19	55
Queensland	Badu Island	Yes	90	53	10	178	95	276
	Bentineck Island	Yes	25	269	5	89	48	138
	Boigu Island	Yes	7.8	6	55	977	524	1519
	Darnley Island	Yes	70	195	0	18	10	28
	Dunk Island	Yes	4	170	1	18	10	28
	Goold Island	Yes	15	101	1	18	10	28
	Hammond Island	Yes	18	104	3	53	29	83
	Horn Island	Yes	16.7	396	8	142	76	221
	Macleay Island	Yes	3	16	0.7	12	7	19
	Magnetic Island	Yes	6.3	6	2	36	19	55
	Moa Island	Yes	52	72	21	373	200	580
	Moreton Island	Yes	20	7	54	959	514	1491
	Mornington Island	Yes	29	1662	102	1812	971	2817
	North Stradbroke Island	Yes	3.8	1001	105	1865	1000	2900
	Prince of Wales Island	Yes	16	148	27	480	257	746
	Sweers Island	No	30	7	4	71	38	110
Northern Territory	Bathurst Island	No	61	235	137	2434	1305	3783
	Centre Island	Yes	7.8	64	20	355	190	552
	Croker Island	No	3	11	152	2700	1447	4197
	Groote Eylandt	No	45	42	203	3606	1933	5606
	Marchinbar Island	No	21	5	59	1048	562	1629
	Melville Island	No	24	2	1054	18724	10036	29106
	North Island	Yes	28	13	3	53	29	83
	Peron Island	No	3.4	3	3	53	29	83
	Raragala Island	No	36	52	11	195	105	304
	Vanderlin Island	Yes	7	6	68	1208	647	1878
	West Island	Yes	4	576	30	533	286	828
	Yabooma Island	No	2.7	2	3	53	29	83

value and the presence of species listed under the Environment Protection and Biodiversity Conservation Act (Department of the Environment and Energy [DEE] 1999). To ascertain feasible islands for quarantine, we refine this list to include only islands that are ≥ 2 km from the Australian mainland and occur within the potential distribution of cane toads in Australia (Kearney et al. 2008). For each island in our dataset, we map the length of permanent freshwater shoreline available, using either satellite maps, government/landholder records, or a combination of both – resulting in a net kilometer length of shoreline for each island in our dataset (Table 2). We apply our survey effort per unit length that our estimates are based upon across the resultant length of shoreline. For islands in our dataset which possess a large length of shoreline we assume organizations have adequate staff to maintain the survey effort on which our estimates are based (see field sampling). All islands were cross-checked for the presence of cane

toads via the 'Feral Animals on Offshore Islands' database (DEE, 2016) in addition to the presence of human settlement. In cases where islands had no permanent freshwater but did have human settlement (or known livestock presence), a one-kilometer circumference was assumed around dwellings and visible watering points.

In addition to the islands derived from this report, we explore the value of a potential cane toad containment strategy outlined in a revised version of the Cane Toad Threat Abatement Plan (Tingley et al. 2013). This strategy aims to develop a 'waterless barrier' on the Australian mainland by excluding cane toads from artificial water bodies on cattle stations between Broome and Port Hedland in Western Australia. If implemented successfully, this strategy could keep toads out of the Pilbara (and subsequent regions) – an effective quarantine of 268 000 km^2 of the Australian mainland (see Florance et al. 2011; Tingley et al. 2013; Southwell et al. 2017 for further information). Using a dataset on the presence of bore holes, cattle watering points, dams, and permanent freshwater bodies in the Pilbara Bioregion (see Southwell et al. 2017) we estimate the economic benefit of the proposed barrier. A one-kilometer circumference was applied to all waterpoints, dams and pools, in addition to a per-kilometer of shoreline rate along permanent watercourses within the region.

Results

The number of cane toads removed from both Horan and Indian Island, c_t, declined over time (Figure 1). Across the duration of our surveys, we captured and removed a total of 1550 cane toads (1251 on Horan Island, 299 on Indian Island). The estimated posterior probability of detecting an individual toad on a given night differed between our two study sites (Horan Island: mean p [95% credible interval] = 0.10 [0.07, 0.13]; Indian Island: 0.27 [0.22, 0.33]) (Suppl. material 4: Figure S3). Given site-specific detection probabilities, the estimated number of toads present at the initiation of our surveys (N_0) was much higher on Horan Island (2696 [2183, 3549]) than on Indian Island (353 [308, 407]) (Suppl. material 5: Figure S4).

Horan Island – situated in a freshwater lake – has a circumference of 7.63 km, which translates to a cane toad density of 352 [287, 466] individuals per kilometer of freshwater shoreline. The freshwater source on Indian Island has a circumference of 1.04 km, translating to a density of 341 [298, 391] individuals per kilometer of freshwater shoreline. We could also express toad density as animals per km^2 of island, in which case we calculate an average density of individuals of 56/km^2 on Indian Island and 2899/km^2 on Horan Island.

Cost Sensitivity

Applying our parameter estimates derived from our Horan Island site, we estimate a removal cost of $22 487 [$14 691, $34 480] per kilometer of freshwater shoreline, or

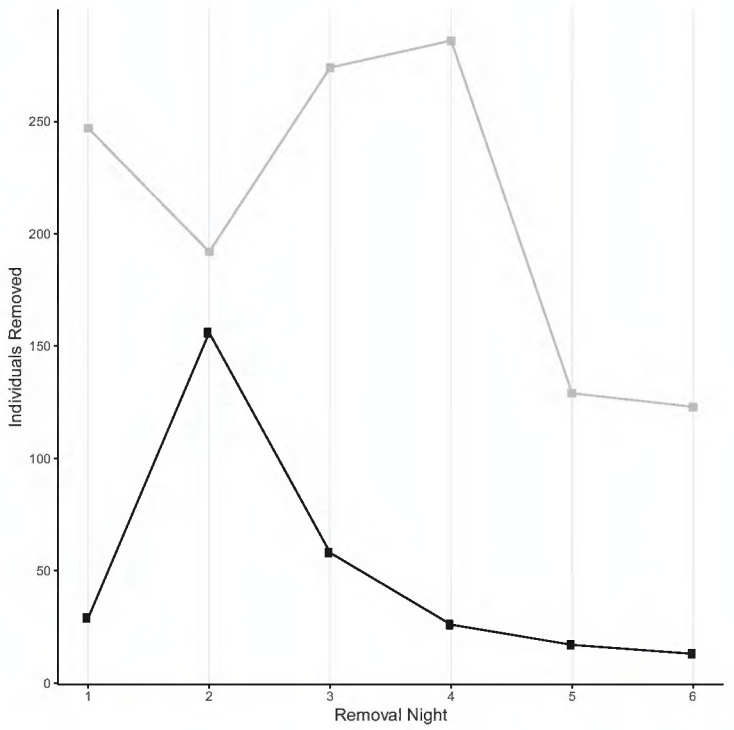

Figure 1. Numbers of individual cane toads captured per night on Horan (gray) and Indian (black) Islands.

$184 564 [$120 582, $282 998] per km^2 of land. Using the values derived from our Indian Island site, we estimate it would cost $39 724 [$22 069, $64 001] per kilometer of freshwater shoreline, or $6 559 [$3 644, $10 568] per km^2 of land.

Benefit of quarantine on Prioritized Australian Islands

Using our estimates of eradication costs per-kilometer of freshwater shoreline, we examine the economic benefit of cane toad quarantine on all toad-free islands (by jurisdiction), as well as the cost to restore all toad-inhabited islands to a toad-free state (Figure 2). The current economic benefit of quarantine on all prioritized toad-free islands is estimated to be between $43.4 [28.4–66.6] million (based on Horan Island) and $76.7 [42.6–123.6] million (Indian Island). We estimate it would cost, on average, between $6.0 [3.9–9.2] million (Horan Island) and $10.6 [5.9–17.0] million (Indian Island) to remove toads from all prioritized islands currently occupied by toads. Finally, we estimate the economic benefit of the 'waterless barrier' protecting the Pilbara to be between $80.5 [52.6–123.4] million (Horan Island) and $142.1 [79.0–229.0] million (Indian Island).

Discussion

As the number of alien invasive species requiring management increases, practitioners must identify efficient strategies for allocating resources to various management activities. Although conventional wisdom places emphasis on prevention measures, the practice of valuing such actions in the face of non-economic costs can be challenging.

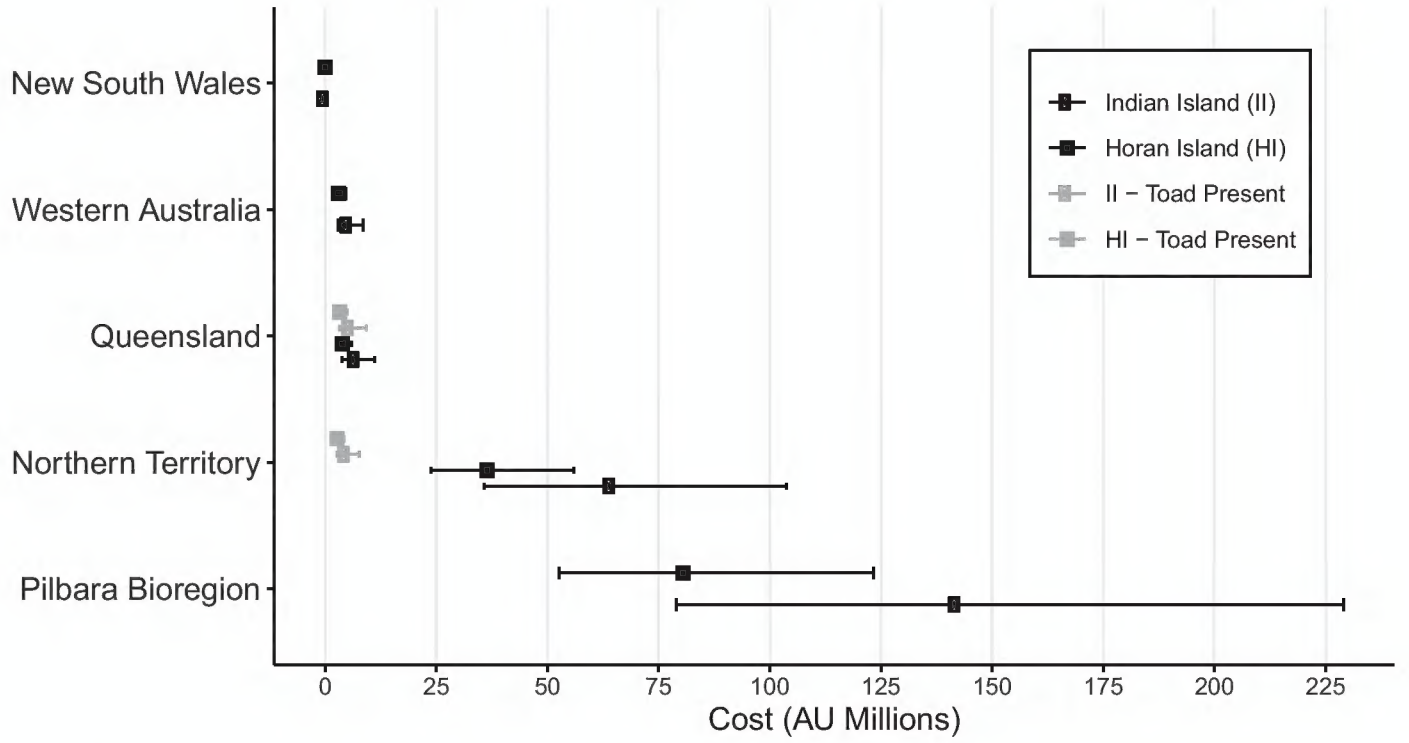

Figure 2. Distribution of the benefit of cane toad quarantine across different jurisdictions within Australia. Toad present distributions denote areas where toads are known to occur and represent the cost to remove toads. No islands in either New South Wales, Western Australia or the Pilbara Bioregion have confirmed toad presence.

Placing monetary value on a conservation benefit will most often require some value judgement as to the monetary worth of biodiversity. Using estimates of a species' detectability, population density, and subsequent eradication costs, we aim to sidestep such value judgement when investigating the benefit of quarantine measures in combatting the impact of the invasive cane toad across Australia's prioritized offshore islands.

Despite substantial community and research effort into cane toad removal via trapping and hand capture, there are only a handful of published detection estimates for the species (Griffiths and McKay 2007). Our detection estimate is, of course, specific to the details of our survey. Nonetheless, it is surprisingly low for our large-shoreline site (Horan Island). Here, the length of shoreline meant we only passed each location once per night, and individual toads in this closed system had, on average, a 0.10 [0.07–0.13] probability of being seen on any given night. This contrasts with our small-shoreline site (Indian Island), where we were able to make multiple passes of the same point each night. Here, individual toads had a 0.27 [0.22–0.33] probability of being detected on a given survey night. Whilst individual toads are relatively easy to see when they are active, our results suggest that this might give a misleading impression of their detectability, especially if the size of area surveilled prevents more than a single pass during each survey. Additionally, physiological correlates are likely to affect individual detection probability, with both sex and body condition linked to activity levels (and hence detectability) of adult cane toads (Yeager et al. 2014). Further work is required to examine how both physiological and environmental correlates influence cane toad detectability as they invade into, and interact with novel environments in Australia.

We compared two density metrics: linear density (per km) and areal density (per km^2). Our areal density estimate for Horan Island (2 893 individuals/km^2) is similar to estimates derived from previous studies of invasive cane toads in the Solomon Islands archipelago (1 035/km^2; Pikacha et al. 2015), the islands of Papua New Guinea (3 000/km^2; Zugg et al. 1975; Freeland et al. 1986), and density estimates of an analogous invasive toad on Madagascar (3 240/km^2; Reardon et al. 2018). A single study conducted on the Australian mainland reported densities as high as 256 300 individuals per km^2 (Cohen and Alford 1993), but this estimate was predominantly of the metamorph life stage, which occurs at very high densities prior to dispersal. Metamorphs are strongly constrained to the edges of water bodies (Child et al. 2008), and typically suffer high mortality from predation and desiccation before reaching maturity (Ward-Fear et al. 2010). While an areal density would make sense in a habitat where animals are constrained by some factor that scales with area (e.g., primary productivity), it is clear that toads in northern Australia are often constrained by access to water in the dry season, and thus length of shoreline is more appropriate. Length of shoreline not only defines access to water, but also the density of infectious parasites (such as *Rhabdias pseudosphaerocephala*) that use moist conditions and high toad densities along shorelines as opportunities for transmission (Kelehear et al. 2011, 2013). It is also likely that the survival rate of emergent metamorphs is dependent on length of shoreline, because this will set the density of conspecifics and so moderate the rate at which these conspecifics cannibalize each other (Pizzatto and Shine 2008). In comparing the areal and linear densities between our sites, we find a large difference between sites in the areal metric, but a strikingly similar density value across sites in the linear metric. Our results suggest that across these two different systems, adult toads achieve a density of around ~350 adults per kilometer of shoreline.

Because toads in dry conditions require regular re-hydration (Seebacher and Alford 2002; Tingley and Shine 2011) it is a logical step to conduct removal efforts when toads are restricted to a subset of semi-permanent hydration points during drier sections of the year (Letnic et al. 2015). Given the ecological reasons discussed above, and the fact that the linear density metric is so concordant across sites, we suggest that the linear metric should be used to calculate eradication costs. Certainly, if we use the areal metric, we find a wide gulf in the possible eradication values relative to our shoreline metric (Suppl. material 3: Figure S2). Encouragingly, our cost estimates using the shoreline metric are similar to estimates derived from a successful eradication program associated with removing the American bullfrog from two locations in Canada ($8 200–$23 000 CAN per kilometer of freshwater shoreline).

To our knowledge, there is only one instance in which the cost to eradicate cane toads from an island has been documented (Wingate 2011). Carried out on Nonsuch Island in Bermuda, this removal occurred over six years and included countless volunteer hours, hand collection and fencing methods, and an investment of $10 000 USD (~$14 330 AUD) to remove toads from an area of 0.6 km^2. In addition, two successful eradications from extralimital mainland sites have been documented, occurring beyond

the southern border of the cane toads' current range in Australia (White 2010; Greenlees et al. 2018). The low incidence of successful removals of the invasive cane toad mirrors a broad trend in the eradication of invasive amphibian populations globally (Adams and Pearl 2007; Kraus 2009; Beachy et al. 2011; Orchard 2011). As such, there is scant information available to guide policy makers and management agencies when evaluating the feasibility of implementing amphibian quarantine and eradication measures.

Hand removal of individuals is required if eradication is to be successful. In landscapes where hydration points are localized or scarce, the use of fencing to exclude individuals from waterbodies can be a cost-effective solution (e.g., Wingate 2011). In these cases, the effectiveness of fencing relies predominantly on the proportion of the population excluded outside the fence (those not excluded still need to be removed by hand), as well as the cost of materials and the person hours associated with installing and maintaining the fence (see Brooke et al. 2004 for a full costing). For small waterbodies where fencing is feasible, the cost will be directly reduced by the proportion of the population retained outside the fence. Our goal was to provide a general cost metric comparable across prioritized islands and jurisdictions, and to place a lower bound on the value of cane toad quarantine more generally. As such, we refrain from exploring a multi-method approach, although acknowledge this may reduce the overall cost of an eradication program in some instances.

If we are to shift away from tactical, post-invasion approaches, to a preventative strategic approach, management practitioners require an estimate of the economic value that quarantine holds. Our analysis of the feasibility and benefit of cane toad quarantine is timely, given renewed emphasis on Australia's offshore islands as safe havens to buffer biodiversity against cane toad impacts. Sixty-two Australian offshore islands designated as 'high conservation status' fall within the cane toad's predicted distribution; more than a third of these (21) have already been colonized by toads. Given our criteria (see Methods), we estimate the remaining value of toad quarantine across toad-free islands in northern Australia to be up to $77 [43–124] million. This value is conservative for a number of reasons. It is a reasonable expectation that as islands become home to increasing numbers of insurance populations or endangered species, the benefit of maintaining those islands as pest-free (measured as the cost of restoration) will increase. In addition, as toads establish themselves in an increasing number of these islands, those remaining toad-free will, by their scarcity alone, attain a greater environmental value.

At the same time, our estimate of the remaining value of toad quarantine across toad-free islands may overestimate the total quarantine benefit because it is unlikely that all islands without quarantine will be invaded. For example, islands that only contain hydration opportunities in the form of cultivated lawns or watering gardens (e.g., Darnly Island, Table 2) may be suitable for toads to invade, but reproduction and long-term persistence are unlikely. The benefit of quarantine within our dataset is held primarily by a few large islands (e.g., Melville Island, Table 2). These larger islands often have human settlements, competing management objectives (e.g., economic growth activities, multi-species quarantine), or more convoluted invasion pathways associated

with anthropogenic activity. For those that contain large human settlements, the use of organized community groups to conduct local removals or population suppression may reduce costs, although eradication is unlikely without a defined management goal and coordinated effort. In short, quarantine needs to be prioritized and carefully managed on these large islands.

Eradication efforts for taxa other than toads have been successful on large islands, such as a goat eradication program on Santiago Island (5 465 km^2 at a cost of $7.08 million) (Cruz et al. 2009) or rat eradication carried out on Macquarie island (128 km^2 at a cost of $21.25 million) (Raymond et al. 2011). These efforts on larger islands require careful planning, intersectional management, and investment in post-eradication surveillance and monitoring (Moore et al. 2010; Rout et al. 2011; Carwardine et al. 2012) and the monetary cost associated with a successful eradication will vary depending on the biology of the target species in question.

The vanguard of the cane toad invasion is currently sweeping across Western Australia at ~50 km per annum, but recent research suggests that a waterless barrier between the Kimberley and the Pilbara could halt the toad invasion (Florance et al. 2011; Tingley et al. 2013; Southwell et al. 2017; Gregg et al. 2019). This barrier represents the only option remaining to exclude cane toads from realizing their entire potential distribution across the Australian mainland. Applying our results to this management strategy revealed that the benefit of quarantine over such an area ($80–142 M) is roughly double the value of quarantine across all offshore islands combined ($49–77 M). The cost of quarantine in this case has been rigorously estimated at around $5 million dollars over 50 years (Southwell et al. 2017), only a fraction of what we estimate it would cost to eradicate toads from this area.

Here we demonstrate the immense benefit of toad quarantine across northern Australia. We avoid value judgement and simply calculate the cost of eradication in the case of quarantine failure. Our valuation is certainly a lower bound on the true benefit, but valuing preventative management is important and will become more so as conservation actions increasingly rely on offshore islands and fenced areas as cost-effective avenues to protect biodiversity from the impacts of alien invasive species. Quarantine measures often protect against multiple potential invaders but our results suggest that even when considering a single species, the monetary value of quarantine can be substantial. Prevention, it seems, is worth more than we might naively guess, even with aphorisms to remind us.

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Supplementary material 1

File S1

Authors: Adam S. Smart, Reid Tingley, Ben L. Phillips

Data type: statistical data

Explanation note: Working to support the formulation of the critical removal threshold (r_{crit}) – the number of days required to reduce a population to less than two individuals.

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Link: https://doi.org/10.3897/neobiota.60.34941.suppl1

Supplementary material 2

Figure S1. Estimated density of cane toads on each island using density calculated per km of shoreline, and per km^2 of landmass

Authors: Adam S. Smart, Reid Tingley, Ben L. Phillips

Data type: statistical data

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Link: https://doi.org/10.3897/neobiota.60.34941.suppl2

Supplementary material 3

Figure S2. Costs of eradication calculated per km of shoreline and per square kilometre of landmass

Authors: Adam S. Smart, Reid Tingley, Ben L. Phillips

Data type: statistical data

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Link: https://doi.org/10.3897/neobiota.60.34941.suppl3

Supplementary material 4

Figure S3. Posterior distributions of the detection probabilities of cane toads on Horan and Indian Islands

Authors: Adam S. Smart, Reid Tingley, Ben L. Phillips

Data type: statistical data

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Link: https://doi.org/10.3897/neobiota.60.34941.suppl4

Supplementary material 5

Figure S4. Posterior distributions of cane toad population size (N_0) before removal effort

Authors: Adam S. Smart, Reid Tingley, Ben L. Phillips

Data type: statistical data

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